EVIDENCE FOR A NARROW STRUCTURE AT W$\sim$1.68 GEV IN ETA PHOTOPRODUCTION ON THE NEUTRON

Viacheslav Kuznetsov[1] for the GRAAL Collaboration

Institute for Nuclear Research, 117312 Moscow, Russia

Abstract

Recent updates in the analysis of quasi-free η photoproduction on the neutron and proton bound in a deuteron target are presented. The $\gamma n \to \eta n$ quasi-free cross section reveals a bump-like structure which is not seen in the cross section on the proton. This structure may signal the existence of a relatively narrow ($M \sim 1.68$ GeV, $\Gamma \leq 30$ MeV) baryon state. Its properties, the possibly narrow width and the strong photocoupling to the neutron, look surprising.

Despite the availability of modern precise experimental data, the spectrum of baryons is not yet well established. Among 43 nucleon and Delta resonances predicted by QCD-inspired models, almost half have yet to be experimentally identified ("missing" resonances)[1]. Quantum chromodynamics may also allow for more complicated quark systems containing, for example, an additional quark-antiquark pair $q\bar{q}$ (pentaquarks). The existence (or non-existence) of this type of particles is another challenge for both theory and experiment.

Much of knowledge on the baryon spectrum was obtained through pion-nucleon scattering and meson photoproduction on the proton. Meson photoproduction on the neutron may offer a unique tool to study certain baryons which have still been poorly explored. For example, a single-quark transition model[2] suggests only weak photoexcitation of the $D_{15}(1675)$ resonance from the proton target. On the other hand, photocouplings to the neutron calculated in the framework of this approach are not small.

[1]E-mails Slava@cpc.inr.ac.ru, SlavaK@jlab.org

Possible photoexcitation of the non-strange pentaquark state (if it exists) is of high interest as well. This particle is associated with the second nucleon-like member of an antidecuplet of exotic baryons[3, 4]. Evidence for the lightest member of the antidecuplet, the $\Theta^{+}(1540)$ baryon, is now being widely debated[5]. A benchmark signature of the non-strange pentaquark could be its photoproduction on the nucleon. Exact $SU(3)_F$ would forbid the proton photoexcitation into the proton-like antidecuplet member. The chiral soliton model predicts that photoexcitation of the non-strange pentaquark has to be suppressed on the proton and should occur mainly on the neutron, even after accounting for $SU(3)_F$ violation[6]. The mass of the non-strange pentaquark is expected to be near 1.7 GeV[4, 7, 8], with the total width about 10 MeV and the partial width for the πN decay mode less than 0.5 MeV[8].

Among various reactions, η photoproduction on the neutron is particularly attractive because i) it selects only isospin $I = \frac{1}{2}$ final states; ii) there is enough accurate data for the "mirror" $\gamma p \to \eta p$ reaction; iii) this reaction was considered as particularly sensitive to the signal of the non-strange pentaquark [4, 6, 7, 8]. Up to now η photoproduction off the neutron was explored mostly in the region of the $S_{11}(1535)$ resonance from threshold up to $W \sim 1.6$ GeV[9]. The ratio of the $(\gamma n \to \eta n)/(\gamma p \to \eta p)$ cross sections was extracted and found almost constant near $\sim$0.67. At higher energies, the GRAAL Collaboration reported the sharp rise of this ratio[10].

In this report, the extended analysis of data collected at the GRAAL facility[11] is presented. Both quasi-free $\gamma n \to \eta n$ and $\gamma p \to \eta p$ reactions were explored simultaneously in the same experimental run, under the same conditions and solid angle using a deuteron target. Two photons from $\eta \to 2\gamma$ were detected in the BGO ball[12]. The η-meson was identified by means of their invariant mass and its momentum was reconstructed from the measured photon energies and angles. Recoil nucleons (neutrons or protons) were detected in two sets of detectors:

i) Neutrons and protons emitted at forward angles $\Theta_{lab} \leq 23°$, passed through two planar multiwire chambers, a time-of-flight (TOF) hodoscope made of thin scintillator strips, and a lead-scintillator sandwich TOF wall[13]. The latter detector provides the detection of neutrons with an efficiency of $\sim 22\%$, an angular resolution of $2-3°$(Full Width at a Half of Maximum), and a TOF resolution $600-800ps$ (FWHM). The measurement of TOF makes it possible to discriminate neutrons from photons and to reconstruct neutron momenta;

ii) Recoil nucleons emitted at central angles $\Theta_{lab} \geq 26°$, were detected in the BGO ball[12]. This detector provides partial discrimination of neutrons from photons and no TOF measurement. The neutron energy was obtained using kinematics constraints.

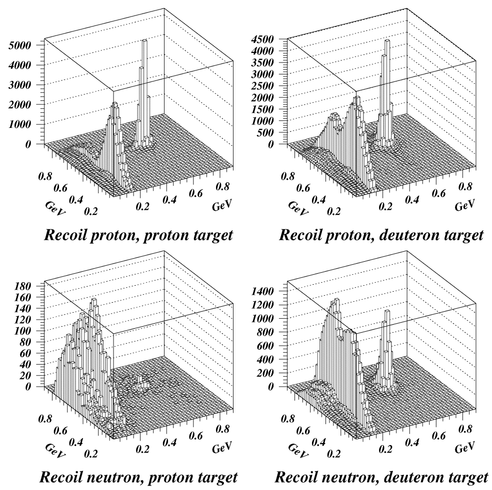

Figure 1: Bi-dimensional spectra of invariant mass of two photons (X axis) versus missing mass $MM(\gamma N, N)$ calculated from momenta of recoil nucleons and the incoming photon (Y axis) for proton and deuteron targets.

As a first step of the analysis, the identification of the ηn and ηp final states was achieved in a way similar to that used in the previous measurements[14] on the free proton. The measured parameters of the recoil nucleon were compared with ones expected assuming quasi-free reaction in which the photon interacts with only one nucleon bound in the deuteron while the second nucleon acts as a spectator.

At photon energies above 950 MeV, a significant background from $\gamma N \to \eta X N$ was observed. This background was clearly seen in the spectrum of the $MM(\gamma N, \eta)$ missing mass in which it appeared as the second bump shifted to higher mass region from the position of the main peak at 0.94 GeV. To reject this background, the cut on $MM(\gamma N, \eta)$ was imposed. In case of the neutron detection in the BGO ball, this cut was added by lower and upper limits on the BGO signal attributed to a neutron hit $0.014GeV \leq \Delta E \leq 0.5 * T_n$. The latter cut was found efficient to discriminate neutrons from accidental low-energy photons emitted as secondary particles in the detector volume, and from high-energy photons produced in background reactions.

Fig. 1 shows bi-dimensional plots of the $\gamma\gamma$ invariant mass versus the missing mass $MM(\gamma N, N)$ calculated from the momentum of the recoil nucleon (proton or neutron) and the momentum of the incoming photon. The plots have been obtained using data collected in experimental runs with proton and deuteron targets. A peak with coordinates ($X = m_\eta$, $Y = m_\eta$) corresponds to ηN photoproduction. A good ηp signal was obtained with the proton target, while only few ηn events appeared in this run. Signals of the both final states are clearly seen with the deuteron target.

In case of a photon interaction with the nucleon bound in the deuteron, event kinematics is "peaked" around that on the free nucleon. Fermi motion of the target nucleon changes the effective energy of photon-nucleon interaction and affects momenta of outgoing particles. It also complicates discrimination of the background. Part of events may suffer from re-scattering and final-state interaction[16]. Such events might generate an artificial structure in the cross section due to specific effects like virtual sub-threshold meson production followed by an interaction with the spectator nucleon [18].

The goal of the second stage of the analysis was to minimize influence of re-scattering, final-state interaction, or background contamination. For that, the sample of events in which the recoil neutrons/protons were detected in the forward assembly, was used. The strategy at this stage was to study the dependence of spectra of the selected events on cuts. The recoil nucleon missing mass $MM(\gamma N, \eta)$, $TOF_{meas} - TOF_{exp}$, and $\Theta_{meas} - \Theta_{exp}$ selection windows were reduced 2-3 times. Tight cuts preferably reject re-scattering, final-state interaction, and the remaining background. They also suppress those events whose kinematics is strongly distorted by Fermi motion or in which one or more parameters of outgoing particles are not properly measured due to detector response.

Four types of spectra were considered at this stage:

i) The spectrum of the center-of-mass energy reconstructed as the invariant mass of the final-state η and the nucleon $M(\eta N)$. This quantity is not affected by Fermi motion but includes large uncertainties due to experimental resolution ($40 - 60$ MeV(FWHM)).

ii) The spectrum of the center-of-mass energy W calculated from the momentum of the initial-state photon and assuming the target nucleon to be at rest $W = \sqrt{(E_\gamma + M_N)^2 - E_\gamma^2}$. This quantity ignores Fermi motion and is peaked around the real center-of-mass energy.

iii) Distribution of the momentum for the spectator nucleon reconstructed as

the "missing" momentum from the momenta of the final-state η and nucleon and the momentum of the incoming photon;
iv) Difference between the final-state $M(\eta N)$ invariant mass and the initial-state center-of-mass energy W.

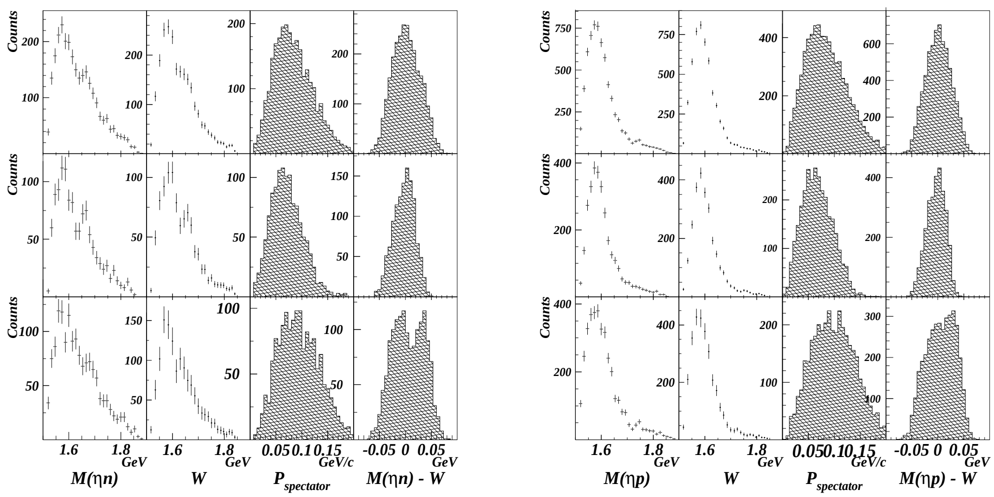

Figure 2: On the left: $\gamma n \to \eta n$ data. On the right: $\gamma p \to \eta p$ data. Spectra of center-of-mass energy, calculated as invariant mass of final-state η and the nucleon (left columns), from the energy of the incoming photon and assuming the target nucleon to be at rest (second columns), momentum of the spectator nucleon (third columns), and difference between final-state and initial-state center-of-mass energies(fourth columns). Upper rows correspond to initial selection, middle rows show spectra after tight cuts, lower rows show events rejected by tight cuts.

The upper row of Fig. 2(left panel) shows the $M(\eta n)$ (first column) and W (second column) spectra obtained with the initial cuts. Both of them exhibit a shoulder-like bump in the region of 1.6 - 1.7 GeV on the slope of the $S_{11}(1535)$ resonance. The spectator-momentum (third column) and the $M(\eta n) - W$ distributions (fourth column) are relatively broad. Plots in the medium row correspond to the tight cuts. The spectator-momentum spectrum is more compressed. The $M(\eta n) - W$ spectrum is more narrow and is localized near 0. The bumps observed in the previous $M(\eta n)$ and W spectra, become well pronounced and are transformed into peaks near 1.68

GeV. On the contrary, events rejected by the second-level cuts (lower row) form broader spectator momentum distribution with the maximum near 0.1 GeV/c. The $M(\eta n) - W$ difference contains two maxima, both shifted from 0. The $M(\eta n)$ and W spectra show some hints on lateral peaks.

The same procedure was applied to the quasi-free $\gamma p \to \eta p$ reaction (the right panel of Fig. 2). The spectator momentum and $M(\eta p) - W$ spectra are similar to those obtained on the neutron. However, the $M(\eta N)$ and W spectra are smooth and exhibit no structure.

Evolution of spectra in Fig. 2 suggests that most of events rejected by the second-level cuts either stronger suffer from Fermi motion and/or detector response, or possibly originate from re-scattering and final-state interaction. On the contrary, events shown in the middle-row plots, correspond to quasi-free reactions. These spectra clearly reveal a peak at 1.68 GeV in η photoproduction on the neutron which is not seen on the proton.

The measured quasi-free differential cross sections for ηn and ηp photoproduction are shown in Fig. 3. The common normalization was done by comparing quasi-free proton data at backward angles with the E429 solution of the SAID $\gamma p \to \eta p$ partial-wave analysis[19] and η - MAID prediction[15] for η photoproduction on the free proton, which were folded with Fermi motion (upper row, right panel of Fig. 3). Error bars shown in Fig. 3 correspond to statistical uncertainties only. The normalization uncertainty of 10% originates mostly from the quality of simulations of quasi-free processes and from uncertainties in determination of the neutron detection efficiency. At backward angles, a good coincidence in the shape of the cross section on the proton and the SAID and MAID solutions was obtained (right panel of Fig. 3). At more forward angles, re-scattering and final-state interaction seem to become more significant in the region of the $S11(1535)$ resonance.

The cross section on the neutron clearly reveals a bump-like structure[2] near $W \sim 1.68$ GeV. This structure is better pronounced at central angles around 90°. At more forward angles, another wide enhancement seems to appear at higher energies above 1.7 GeV. The data have been compared with an isobar model for η photo- and electroproduction $\eta - MAID$[15]. The model includes 8 main resonances and suggests the dominance of the $S_{11}(1535)$ and $D_{15}(1675)$ resonances in η photoproduction off the neutron

[2]The cross section obtained with tight cuts exhibit a slightly more narrow structure but includes larger statistical and systematic errors. For the sake of simplicity and reliability of conclusions it is not shown.

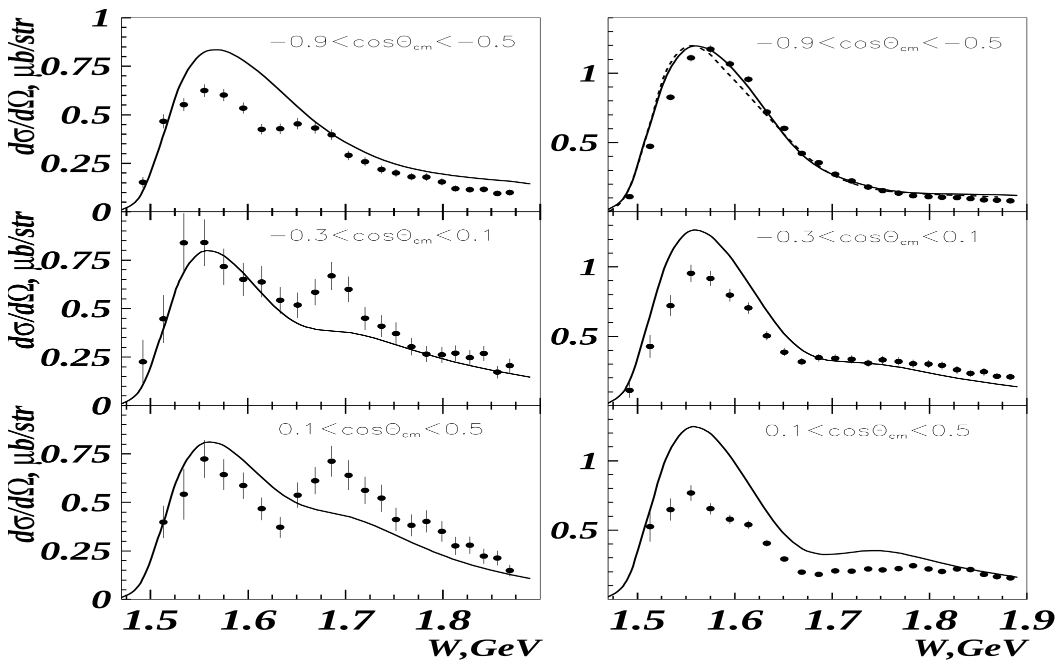

Figure 3: Quasi-free differential cross-section at different angles . Right panel: $\gamma p \to \eta p$. Left panel: $\gamma n \to \eta n$. Solid lines are η-MAID prediction for η photoproduction on the free neutron/proton folded with Fermi motion. Dashed line is E429 solution of the SAID $\gamma p \to \eta p$ partial wave analysis folded with Fermi motion.

below $W \sim 1.75$ GeV. The model predicts a bump-like structure near $W \sim 1.7$ GeV in the total η photoproduction cross section on the neutron[20]. This structure is caused by the $D_{15}(1675)$ resonance. The η - MAID differential cross sections are smooth (Fig. 3, left panel). The PDG estimate for the $D_{15}(1675)$ ηN branching ratio $\frac{\Gamma_{\eta N}}{\Gamma_{total}}$ is close to 0 while the value included into the η-MAID is 17%[20]. The PDG average for the Breit-Wigner width of this resonance is $\Gamma \sim 150$ MeV[1]. The structure observed in the quasi-free cross section looks more narrow.

It is well known that η photoproduction on the proton is dominated by photoexcitation of the $S_{11}(1535)$ resonance up to $W \sim 1.68$ GeV. At higher energies, the increasing role of higher-lying resonances is expected [14, 17]. η photoproduction on the neutron is dominated by the $S_{11}(1535)$ up to $W \sim 1.62$ GeV[9, 10]. The shape of cross sections on the neutron and on the

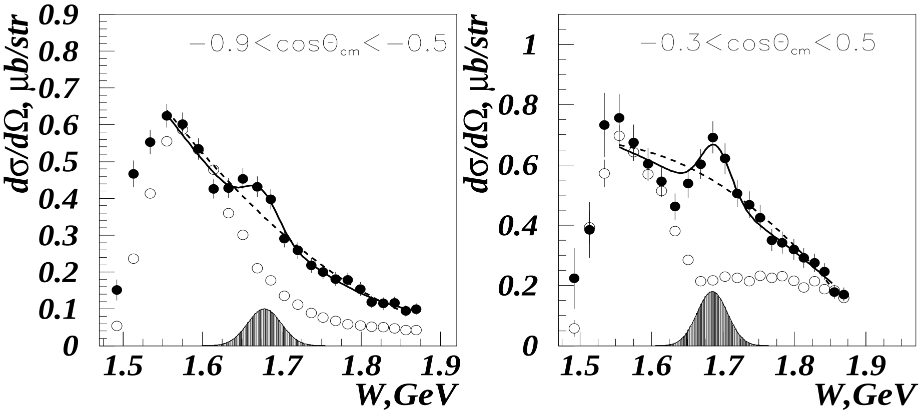

Figure 4: Polynomial-plus-narrow-state fit of $\gamma n \to \eta n$ cross sections. Black circles are $\gamma n \to \eta n$ data. Open circles are $\gamma p \to \eta p$ cross section normalized on the cross section on the neutron in the maximum of the $S_{11}(1535)$ resonance. Dashed areas show simulated contribution of the narrow state. Solid lines are the result of the fit. Dashed lines show the fit by 3-order polynomial only.

proton in the region $S_{11}(1535)$ resonance below $W \sim 1.62$ GeV is similar (Fig. 4). One may assume that the enhancement in the cross section on the neutron at $W \sim 1.62 - 1.7$ GeV is caused by an additional relatively narrow resonance. In Fig. 4 the simulated contribution of a narrow state ($M \sim 1.68$ GeV, $\Gamma = 10$ MeV) is shown. This state appears as a wider bump in the quasi-free cross section due to Fermi motion of the target neutron. The neutron cross section in the range of $W \sim 1.55 - 1.85$ GeV is well fit by the sum of the third-order polynomial and a narrow state, with the overall χ^2 about 11/14 and 12/14 for the backward and central angles respectively. The fit by only third-order polynomial increases χ^2 to about 31/15(29/15).

Thus, the apparent width of the structure in the $\gamma n \to \eta n$ cross section is close to one expected due to smearing by Fermi motion. The same structure was observed in the $M(\eta n)$ invariant mass spectra(Fig. 2). The width of the peaks in the $M(\eta n)$ spectra is also close to experimental resolution. Therefore this structure may signal the existence of a relatively narrow ($\Gamma \leq 30$ MeV) state. In general, such state coincides with the expectation of the Chiral Soliton Model[6, 7] and modified PWA[8] for the non-strange pentaquark. On the other hand, the manifestation of one of usual resonances is not ruled out. If so, its properties, the possibly narrow width and the strong photocoupling to the neutron, look surprising.

The decisive identification of the observed structure requires a complete partial-wave analysis based on a fit to experimental data. New beam asymmetry data from GRAAL[21] and cross sections from the CB/TAPS Collaboration [22] are expected to enlarge the data base. The problem underway is how to fit quasi-free data smeared by Fermi motion and distorted by rescattering and final-state interaction. The use of polarization observables is going to be even more sophisticated: much of theoretical efforts is needed to understand the interaction of polarized photons with bound nucleons[23]. Another way is to search for the signal of this state in other reactions (for example, $\gamma n \to \pi\Delta$ [6]) and/or using polarized targets. New dedicated experiments at JLAB and the upgraded ELSA and MamiC facilities equipped with the Crystal Barrel and Crystal Ball detectors, might be of high importance.

It is a pleasure to thank the staff of the European Synchrotron Radiation Facility (Grenoble, France) for the stable beam operation during experimental run. Our thanks are to Y. Azimov, K. Goeke, and M. Polyakov for the valuable theoretical contribution and the support of this work. Discussions with W. Briscoe, V. Burkert, D. Diakonov, A. Dolgolenko, I. Jeagle, M. Kotulla, B. Krusche, A. Kudryavtsev, V. Mokeev, E. Pasyuk, P. Pobylitsa, M. Ripani, A. Sibirtsev, I. Strakovsky, M. Tauti, L. Tiator and R. Workman were very helpful. This work has been supported by Università degli studi di Catania and Laboratori Nazionale del Zud, INFN Sezione di Catania (Italy), and by Ruhr-Universität Bochum (Germany).

References

[1] S.Eidelman *et al.*, *Phys. Lett.* B**592**, 1 (2004).

[2] V. Burkert *et al.*, *Phys. Rev. C* **67**, 035205 (2003).

[3] D. Diakonov, V. Petrov, and M. Polyakov, *Z. Phys. A* **359**, 305 (1997).

[4] R. Jaffe and F. Wilczek, *Phys. Rev. Lett.* **91**, 232003 (2003) [hep-ph/0307341].

[5] V. Burkert, hep-ex/0510309, and references therein.

[6] M. Polyakov and A. Rathke *Eur. Phys. J A* **18**, 691 (2003) [hep-ph/0303138]; H. C. Kim *et al.*, Phys. Rev. D **71** (2005) 094023,[arXiv:hep-ph/0503237].

[7] D. Diakonov and V. Petrov, *Phys. Rev. D* **69**, 094011 (2004) [hep-ph/0310212].

[8] R. Arndt *et al.*, *Phys. Rev. C* **69**, 0352008 (2004) [nucl-th/0312126].

[9] B. Krusche *et al.*, *Phys. Lett. B* **358**, 40 (1995); V. Heiny *et al.*, *Eur. Phys. J. A* **6**, 83 (2000); J. Weiß *et al.*, *Eur. Phys. J. A* **16**, 275 (2003) [nucl-ex/0210003]; P. Hoffman-Rothe *et al.*, *Phys. Rev. Lett.* **78**, 4697 (1997).

[10] V.Kouznetsov *et al.*, Proceedings of Workshop on the Physiscs of Excited Nucleons NSTAR2002, Pittsburgh, USA, October 9 - 12 2002, Ed. E.Swanson, World Scientific, 2003, pg.267-270.

[11] General description of the GRAAL facility is in V.Bellini *et al.*, *Eur. J. A.* **26**, 299 - 419 (2006).

[12] F. Ghio *et al.*, *Nucl. Inst. and Meth. A* **404**, 71, 1998.

[13] V. Kouznetsov *et al.*, *Nucl. Inst. and Meth. A* **487**, 128, 2002.

[14] J. Ajaka *et al.*, *Phys. Rev. Lett.* **81**, 1787(1998); F. Renard *et al.*, *Phys. Lett. B* **528**,

[15] W.-T.Chiang, S.-N.Yang,L.Tiator, and D.Drechsel, *Nucl. Phys* A **700**, 426 (2002), [hep-0110034], http://www.kph.uni-mainz.de 215 (2002);

[16] A. Baru, A.Kudryavtsev, and V. Tarasov, *Phys. Atom. Nucl.* **67** 743, 2004, arXiv:nucl-th/0301021; A. Sibirtsev, S. Schneider, and C. Elster, *Phys. Rev. C* **65**, 067002 (2002), arXiv:nucl-th/0203039; A. Fix and H. Arenhovel, *Phys. Rev. C* **68**, 44002 (2003), arXiv:nucl-th/0203039; and references therein.

[17] M. Dugger *et al.*, *Phys. Rev. Lett.* **89**, 222002 (2002); V. Crede *et al.*, *Phys. Rev. Lett.* **94**, 012004(2004) [hep-ex/0311045].

[18] Y. Ilieva *et al.*,*Nucl. Phys. A* **737**, S158 (2004), [nucl-ex/0309017].

[19] R. A. Arndt, W. J. Briscoe, I. I. Strakovsky, and R. L. Workman, in progress, http://gwdac.phys.gwu.edu.

[20] L.Tiator, Talks at Workshop on the Physics of Excited Nucleons NSTAR2005, Tallahassee, FL, USA, October 12 - 15 2005, and at Workshop on eta photoproduction, Bochum, Germany, February 22 - 25 2006.

[21] Publication in preparation.

[22] J. Jeagle, Talk at Workshop on the Physics of Excited Nucleons NSTAR2005, Tallahassee, FL, USA, October 12 - 15 2005.

[23] A. Sibirtsev, Talk at Workshop on eta photoproduction, Bochum, Germany, February 12 - 15 2006.